Advection Influences on Evapotranspiration of Alfalfa in a Semiarid Climate

Judy A. Tolk,* Steven R. Evett, and Terry A. Howell

ABSTRACT

Advective enhancement of crop evapotranspiration (ET) occurs when drier, hotter air is transported into the crop by wind, and can be an important factor in the water balance of irrigated crops in a semiarid climate. Thirteen days of moderate to extremely high ET rates of irrigated alfalfa (*Medicago sativa* L.) were evaluated using energy balance and atmospheric coupling models to examine the magnitude of ET enhancement due to advection. Alfalfa ET was measured using precise, monolithic weighing lysimeters. The average ET of the selected days was 11.3 mm d^{-1}, with ET exceeding 15 mm d^{-1} on 3 d, with mean 24-h vapor pressure deficit (VPD) of 2.1 kPa and 2-m wind speed of 4.4 m s^{-1}. Evapotranspiration due to available energy (net radiation + soil heat flux) was fairly stable at an average of 6.6 mm d^{-1} whereas advected atmospheric deficits and sensible heat flux (*H*) added as much as 10.5 mm d^{-1} to ET, with *H* providing an average of 42% of the energy used in ET. Overnight ET losses due to continued *H* flux gains and VPD resulted in ET losses as large as 3.0 mm. Advective enhancement of ET plays a significant role in the water balance of the semiarid region of the southern High Plains.

Penman (1948) advanced the theoretical and experimental aspects of evapotranspiration (ET) science with his general equation for the rate of ET from open water, bare soil, and grass. He merged two separate theories concerning evaporation by recognizing that ET estimation required both a thermodynamic equation for surface energy balance and an aerodynamically based vapor transfer equation, making ET a function of the meteorological elements of solar irradiance, air temperature, vapor pressure, and wind (Monteith, 1998). Monteith (1965, 1981) expanded the applicability of Penman's original equation to other surfaces by adding variable resistances to the fluxes of momentum, heat, and water vapor through the plant–atmosphere system based on surface characteristics such as a crop's stomatal and aerodynamic resistances, which came to be known as the Penman–Monteith (P-M) model. The P-M model is now widely used in many variations, e.g., McNaughton and Jarvis (1983) and Allen et al. (2005).

The McNaughton-Jarvis (M-J) model separately calculated the P-M model's energy balance and vapor transfer terms, but also added a weighting, or decoupling, factor Ω which ranged between 0 and 1 (McNaughton and Jarvis, 1983). This factor, which was based on the ratio of surface and aerodynamic resistances, determined the partitioning of ET between the energy balance and vapor transfer terms based on the degree of decoupling from the regional atmospheric conditions. Their equation was written as

$$-\lambda E = \Omega[\Delta(R_n + G)/(\Delta + \gamma)] + (1 - \Omega)[(\rho c_p \mathrm{VPD})/(\gamma\, r_s)] \quad [1]$$

where λE is latent heat flux, R_n is net radiation, and G is soil heat flux, all in W m^{-2} with fluxes toward the surface positive in sign; Δ is the slope of the saturation vapor pressure-temperature curve (kPa $°C^{-1}$); λ is the latent heat of vaporization (J kg^{-1}); ρ is air density (kg m^{-3}); c_p is the specific heat of air at constant pressure (1013 J kg^{-1} $°C^{-1}$); VPD is the vapor pressure deficit (kPa); γ is the psychrometric constant (kPa $°C^{-1}$); r_s is surface (crop and soil) resistance (s m^{-1}) to vapor transport; and Ω is defined as:

$$\Omega = \{1 + [\gamma/(\Delta + \gamma)](r_s/r_a)\}^{-1} \quad [2]$$

where r_a is aerodynamic resistance (s m^{-1}).

In a system where r_a is very large compared with r_s such that Ω tends toward 1, latent heat flux is determined principally by the energy balance term, $[\Delta(R_n + G)/(\Delta + \gamma)]$. The ET rate is effectively "decoupled" from regional atmospheric conditions, implying that the saturation deficit is controlled by physical processes at the surface, and ET is in "equilibrium" (ET_{eq}) with available energy (AE), or $R_n + G$. Conversely, when r_a is small compared with r_s such that Ω tends toward 0, latent heat flux is increased beyond that supplied by AE by the vapor transfer term, $(\rho c_p \mathrm{VPD})/(\gamma\, r_s)$, with the saturation deficit imposed on the surface by the state of the air passing over it (Monteith, 1998). Regionally determined vapor and heat concentrations are advected to the surface by vigorous turbulent mixing by wind, resulting in an "imposed" ET rate (ET_{imp}).

Advection is the transport of an atmospheric property (e.g., vapor, heat) solely by the mass motion of the atmosphere expressed in terms of wind and the atmospheric property and its gradient (Rosenberg et al., 1983). McNaughton and Jarvis (1983) considered the impact of dry or moist air advection on the local equilibrium saturation deficit that would result in either the enhancement or depression of the ET rate. They reported that, for extensive areas of short grass or crops with wet or dry surfaces, the advection component was found empirically to be typically about one-fourth of the radiation component.

Advective enhancement of ET also occurs when sensible heat flux (H, in W m^{-2}) transfers energy toward

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Published in Agron. J. 98:1646–1654 (2006).
Agroclimatology
doi:10.2134/agronj2006.0031

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Abbreviations: AE, available energy ($R_n + G$); DOY, day of year; ET, evapotranspiration; ET_{eq}, equilibrium evapotranspiration; ET_{imp}, imposed evapotranspiration; $ET_{imp\text{-}night}$, nighttime imposed evapotranspiration; LAI, leaf area index; VPD, vapor pressure deficit.

rather than away from the surface, increasing the energy beyond that supplied by AE. The primary components of the surface energy balance are contained in the energy balance equation (Rosenberg et al., 1983), as

$$R_n + H + G + \lambda E = 0 \quad [3]$$

In water deficient areas such as the western USA, advected sensible heat is often a major source of energy used in ET (Abdel-Aziz et al., 1964; Rosenberg, 1969a, 1969b; Hanks et al., 1971; Brakke et al., 1978; Rosenberg and Verma, 1978; Aase and Siddoway, 1982; Devitt et al., 1998; Todd et al., 2000). Irrigated areas represent 'oases' in the drier, unirrigated surrounding landscape (Tanner, 1957). The advected energy and mass can be on such a scale as to affect the ET of the entire irrigated area (regional advection), or be more localized to the border area between adjacent irrigated and nonirrigated fields (local advection). As the distance increases downwind into the irrigated crop from the nonirrigated field (fetch), the influence of local advection decreases until equilibrium λE, or no further change in λE with distance, is achieved. According to Rosenberg et al. (1983), if this equilibrium λE still exceeds AE throughout the field then that difference is the regional advection contribution to ET.

The southern High Plains, or Llano Estacado, lies south of the Canadian River and is one of the largest tablelands on the continent. It is a high, flat, semiarid land covering >8 million ha, with precipitation ranging from about 550 mm yr^{-1} in the east to less than 350 mm yr^{-1} in the west, with annual National Weather Service (NWS) Class A pan evaporation greatly exceeding precipitation. Originally a short grass prairie, the landscape is a now heterogeneous mixture of irrigated and dryland cropland and range lands.

The USDA-ARS Conservation and Production Research Laboratory (USDA-ARS-CPRL) is located on the northern edge of the Llano Estacado with the predominant SSW-SW winds crossing much of that landscape. For many days in the cropping season, daytime 2-m wind speeds exceed 3 m s^{-1} and VPD ranges from 1 to 5 kPa. Periods of below normal rainfall are common, which increases the need for irrigation and further dries the surrounding landscape. The objectives of this research were to examine the influence of advection on moderate to extreme ET events of irrigated alfalfa (*Medicago sativa* L.) in terms of equilibrium and imposed ET as described by McNaughton and Jarvis (1983), and sensible heat inputs as described by Rosenberg et al. (1983).

MATERIALS AND METHODS

The study was conducted in 1998 at the large weighing lysimeter facility located at the USDA-ARS-CPRL at Bushland, TX [35°11′ N; 102°06′ W; 1170 m elev. above MSL]. The soil is classified as Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) (Soil Survey Division, NRCS, USDA, 2003), which is described as slowly permeable because of a dense clayey Bt2 horizon occurring between about 0.3 to 0.5 m below the surface. Predominate wind direction during the study was SW (Fig. 1) and unobstructed fetch (fallow fields,

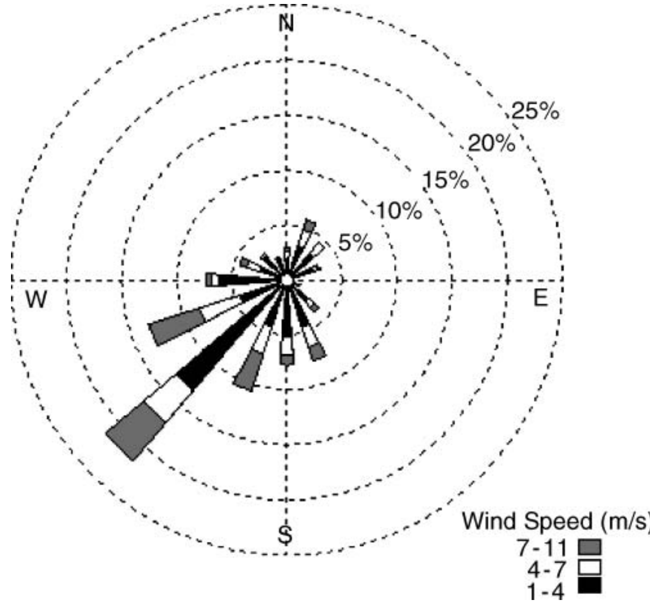

Fig. 1. Wind speed and wind direction analyses for the days included in the study.

dryland cropped areas, or cropland irrigated with center pivots) in this direction exceeded 1 km (Fig. 2).

Alfalfa ('Paymaster 5454') was planted in the autumn of 1995 at a seeding rate of 28 kg ha^{-1} on 0.2-m rows with a double pass to increase plant density. Cutting dates in 1998 were day of year (DOY) 138 (18 May), 174 (23 June), 202 (21 July), 237 (25 August), and 281 (8 October). Alfalfa received 1110 mm in irrigation and/or rainfall over the season, with irrigations being of 20 to 25 mm each usually applied at frequencies of up to three times weekly until about 1 wk before

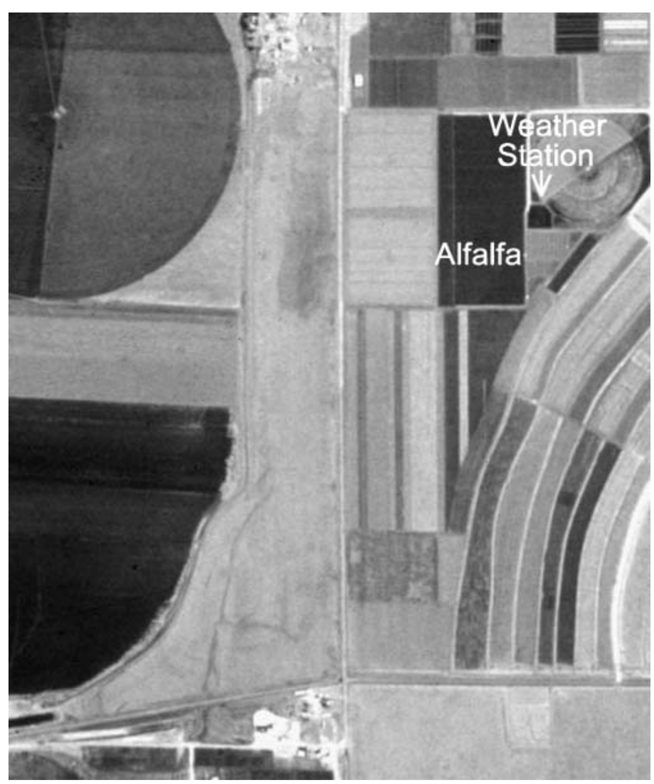

Fig. 2. Aerial view of the alfalfa field and surrounding landscape.

cutting. Irrigation application amounts were selected to fully replace soil water used in ET, with irrigation frequency constrained by time required to irrigate the field and by well capacity. Irrigation frequencies of two to three times per week are typical during peak crop water use periods with the center pivot irrigation systems that irrigate >70% of the irrigation land in the southern Great Plains. Irrigations were applied with a 10-span lateral-move sprinkler system (Lindsay Manufacturing, Omaha, NE) using mid-elevation spray applicators typical of pivots in the region. New nozzles and pressure regulators were installed on each drop (spaced at 1.5 m along the lateral) and nozzle flow rates for nozzles irrigating the lysimeters were checked by mass balance (timed flow into a container that was then weighed). The sprinkler system was aligned N–S, and irrigated E–W or W–E.

Plant samples of four replicate samples of 1 m^2 per field were collected periodically. Leaf area was determined using a leaf area meter (model 3100, Li-Cor, Lincoln, NE). Crop height of each sample was also measured. Daily estimates of crop height needed for parameter calculations as well as of leaf area index (LAI) were made by linear interpolation between samples.

Bias due to cropping differences on the lysimeters or in the fields around the lysimeters was controlled by careful management of planting density, fertilization, irrigation applications, and weeds. Regular visual observation verified that the plant stand and condition were identical on the lysimeters and fields, such that the positions of the lysimeters in the fields could not be determined by observations of the crop. Measurements of lysimeter crop LAI at cutting indicated nearly identical values (well within measurement error).

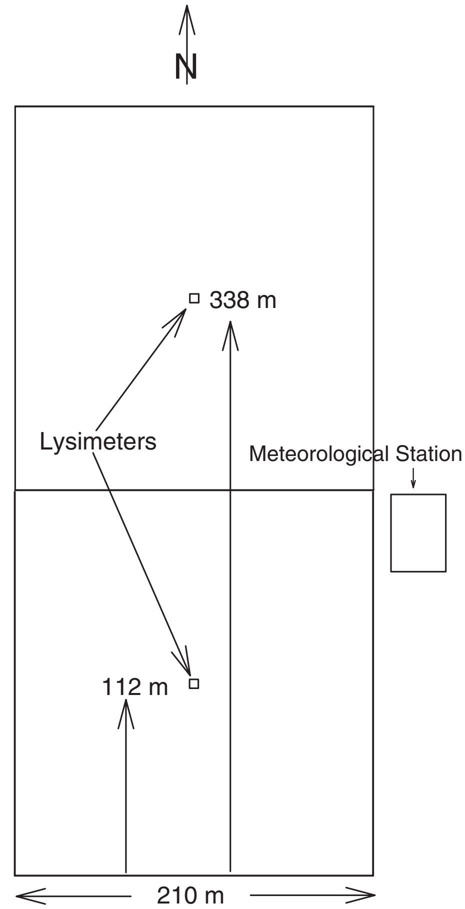

Fig. 3. Layout of the lysimeter field.

Lysimeter Measurements

The ET measurements were made with two large weighing lysimeters (Marek et al., 1988), each located in the center of contiguous 4.7-ha fields (210 m E–W by 225 m N–S) (Fig. 3). The south lysimeter had about 112 m and the north lysimeter 338 m of fetch when wind direction was from the south. Nonirrigated grain sorghum [*Sorghum bicolor* (L.) Moench] and fallow fields were south of the alfalfa, and nonirrigated grain sorghum to the west. The lysimeters each contained a monolithic Pullman core with a 9-m^2 surface area and a 2.3-m depth.

Change in lysimeter mass was determined using a data logger (model CR7-X, Campbell Scientific, Logan, UT) to measure and record the lysimeter load cell (model SM-50, Interface, Scottsdale, AZ) with the signal sampled at 0.5 Hz (2 s) frequency and averaged over 5-min for output. The lysimeters were calibrated using calibration masses traceable to NIST before the experiment. The lysimeter mass measurement accuracy was 0.01 mm, as indicated by the root mean squared error of calibration. To within 0.02 mm, the calibration removed any bias that might have occurred between the two lysimeters due to mass measurement error. Random error of lysimeter measurements was routinely monitored by calculating the standard deviation of mass (and thus change in storage) measurements for every 5-min period. Values of standard deviation were routinely smaller than 0.1 mm, and most were <0.05 mm (Evett, 2002).

Daily (24-h) ET (ET_{24}) was calculated from the difference between mean lysimeter mass losses (from evaporation and transpiration) and lysimeter mass gains (from irrigation or precipitation) divided by the lysimeter area (9 m^2). The amount of irrigation or precipitation was estimated from the mass gain of the lysimeters, or the difference in load cell readings between the beginning and the ending of the event, with the net gain including ET losses occurring during the event. Irrigation amounts were checked against flow meter values, and rainfall amounts were checked against values from rain gauges located at each lysimeter and two rain gauges at the adjacent weather station. Net mass change for each 24-h period was then divided by 9.18 m^2 to find the ET value for the lysimeter area, which included the midpoint between the inner and outer walls (10 mm air gap; 9.5 mm wall thickness; 9.18 m^2 area instead of the 9.00 m^2 lysimeter inside surface area). A pump regulated to -10 kPa provided vacuum drainage, and the drainage effluent was held in two tanks suspended from the lysimeter (their mass was part of the total lysimeter mass) and independently weighed by load cells (drainage rate data are not reported here).

Micrometeorological Measurements

The meteorological mast located at each weighing lysimeter held, among other instrumentation, a cup anemometer (model 014A, Met One, Grants Pass, OR), net radiometer [model Q*5.5, Radiation and Energy Balance Systems (REBS), Seattle, WA], and temperature–humidity probe (model HT225R, Rotronics, Huntington, NY). The anemometer and temperature–humidity probe were at 2 m and the net radiometer at 1 m above the soil surface.

Soil heat flux was measured using heat flux plates (model HFT-1, REBS, Seattle, WA) installed at 50 mm below the soil surface. Soil heat flux at the soil surface was estimated using corrections for heat storage above the heat flux plate that required soil temperature and soil moisture (Evett, 2002). Soil temperature was measured with four pairs of copper-constantan thermocouples (model 304SS, Omega Engineering, Stamford, CT). Each pair had one thermocouple installed at a 10-mm depth and the other at 40 mm, which were wired in parallel to integrate soil temperature. Soil moisture content in the soil layer above the heat flux plate was estimated using the ENWATBAL model (Evett and Lascano, 1993). Meteorological data needed for the weather data input file used in ENWATBAL, including solar radiation, were measured at a weather station about 150 m from the lysimeters (Fig. 2, 3). Also measured at the station was 10-m wind direction (model 024A, Met One, Grants Pass, OR).

Vapor pressure deficit was calculated as the difference between saturation and actual vapor pressure. Saturation vapor pressure was calculated according to Allen et al. (2005), and actual vapor pressure was calculated using Murray's (1967) equation for dew point temperature, using measured 2-m air temperature and relative humidity.

The duplication in instrumentation type among lysimeters and the weather station allowed inter-comparison to monitor individual instrument performance at the time of deployment and throughout the cropping season. The humidity sensors were recalibrated by the manufacturer before deployment, and other instrumentation recalibrated as needed.

Lysimeter load cell and lysimeter micrometeorological instrumentation data were collected by the same data logger for output. The load cell and anemometer signals were averaged for 5 min and the other instrumentation for 15 min and then composited into 30-min means. Both the lysimeter and weather station data were reported on the midpoint of the 30 min, i.e., data were averaged from 0 to 30 min and reported at 15 min.

Resistance and Sensible Heat Flux Calculations

Aerodynamic resistance used in the M-J model was calculated according to Allen et al. (2005) utilizing crop height (CH, in m) and 2-m measurement reference height (Z, in m) given as:

$$r_a = \{\ln[(Z - d)/Z_{om}]\ \ln[(Z - d)/Z_{oh}]\}/(k^2U) \qquad [4]$$

where d is zero plane displacement (0.67 CH, in m), Z_{om} is momentum roughness length (0.123 CH, in m), Z_{oh} is vapor and heat roughness length (0.0123 CH, in m), k is von Karman's constant (0.41), and U is wind speed (m s^{-1}) at reference height Z.

Surface resistance used in the M-J model was calculated by rearranging the P-M model, and converting measured ET averaged over 30 min to λE using the latent heat of vaporization λ (2.45 MJ kg^{-1}), or

$$r_s = [r_a\Delta(R_n + G) + \rho c_p \mathrm{VPD}]/(-\lambda E\gamma) - r_a(\Delta + \gamma)/\gamma \qquad [5]$$

with Δ, ρ, c_p, γ and other related parameters calculated according to procedures described in Allen et al. (2005).

Sensible heat flux was calculated as a residual of Eq. [3], or

$$H = -\lambda E - R_n - G \qquad [6]$$

RESULTS AND DISCUSSION

Total rainfall for 1998 at the research station was 424 mm, which was 50 mm below the average rainfall of 474 mm. However, from DOY 91 (1 April) through DOY 150 (30 May), only about 33 mm of precipitation had occurred at the lysimeter fields and, except for one event of about 20 mm on DOY 145, all other precipitation events were <3 mm each. The cropping season was characterized by consistently above average NWS Class A pan evaporation and below normal rainfall (Fig. 4).

Lysimeter data were selected from DOY 150 through DOY 173 (primarily in June), after which the alfalfa was cut on DOY 174. During the 24-d period, the crops on the lysimeters received about 225 mm in irrigation and 1.4 mm of rainfall. The estimated LAI increased from about 1.1 to about 3.0 and crop height from 0.25 m to 0.6 m. Average daily ET_{24} for the two lysimeters during that 24-d period was 10.1 ($\pm$3.5) mm, wind speed was 4.6 ($\pm$1.2) m s^{-1}, and VPD was 1.9 ($\pm$0.8) kPa. (The $\pm$ number in parentheses following a mean is the standard deviation of the daily mean.)

Of the 24 d, 11 d with irrigation and/or rainfall were eliminated to avoid any errors in the determination of ET, leaving 13 d for evaluation. During the days selected for evaluation, mean daily ET averaged for both lysimeters ranged from about 7.0 mm on DOY 157 to about 17.6 mm on DOY 164, with ET exceeding 15 mm on DOY 164, 167, and 171 (Fig. 5A). For the days that ET was about 12 mm d^{-1} or larger (extreme event days), an irrigation had occurred at about noon on the day before except for DOY 173. The 13-d averages for both lysimeters were 11.0 ($\pm$3.9) mm for ET_{24}, 2.1 ($\pm$0.7) kPa for VPD, and 4.4 ($\pm$1.2) m s^{-1} for wind speed. The difference between lysimeters for ET_{24} ranged from 0.06 to 0.90 mm with an average difference of 0.28 ($\pm$0.26) mm with the south having the larger values except on DOY 151. Similarly, Todd et al. (2000) used inter-calibrated Bowen ratio (BR) systems to show that estimates of ET from the Bowen ratio averaged 5% larger at the south lysimeter when one system was located at the north lysimeter and one at the south lysimeter in 1998. The differences were greatest early in the season and when winds were southerly and there was evidence of sensible heat advection ($\lambda E > R_n + G$). When winds were westerly and there was no evidence of sensible heat advection, differences in the BR were essentially null. The difference between lysimeters for VPD (Fig. 5B) ranged from 0 to 0.15 kPa with an average difference of 0.04 ($\pm$0.06) kPa, whereas the difference in wind speed (Fig. 5C) ranged from 0.0 to

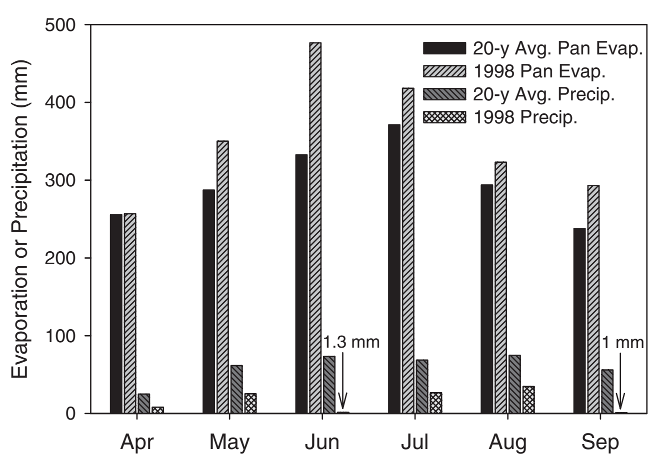

Fig. 4. The 20-yr average and 1998 Class A pan evaporation and precipitation for the cropping season.

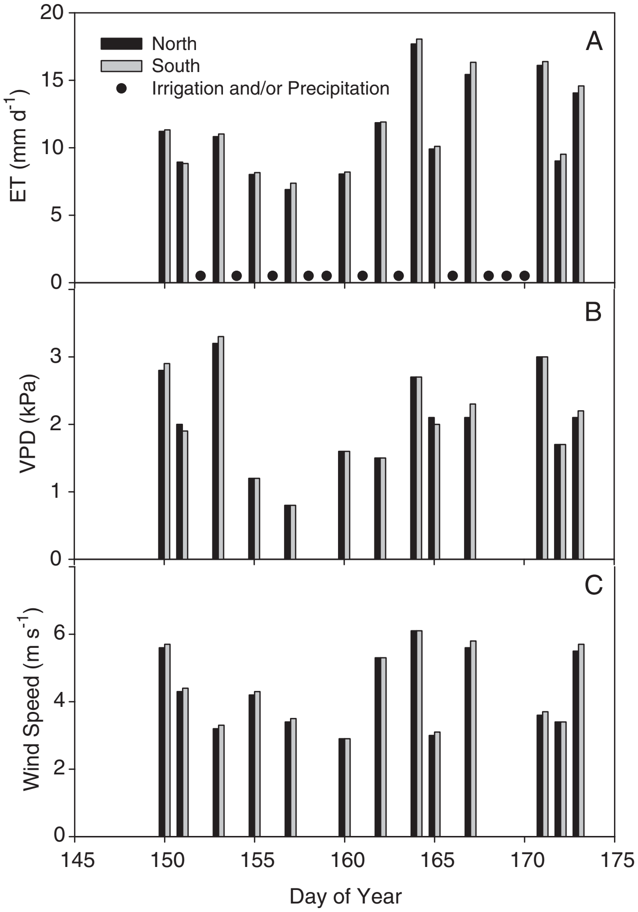

Fig. 5. (A) Daily evapotranspiration (ET), (B) average vapor pressure deficit (VPD), and (C) wind speed for the north and south lysimeters for the days used in the analyses.

0.2 m s^{-1} with an average difference of 0.1 ($\pm$0.1) m s^{-1}. Unless otherwise noted, data reported hereafter will be an average of the parameter for both lysimeters.

Extreme ET events occurring during the 24-d period that were eliminated due to irrigation were 16.0 mm on DOY 168, 12.2 mm on DOY 169, and 11.8 mm on DOY 170. Other reported extreme ET events of irrigated alfalfa occurring elsewhere were 14.2 mm d^{-1} during an extreme drought period at Mead, NE (Rosenberg and Verma, 1978), and 12 mm d^{-1} at Kimberly, ID (Wright and Jensen, 1972), both measured using weighing lysimeters. Also reported was about 11 mm for the daylight hours at Phoenix, AZ (van Bavel, 1967). Wright (1988) reported that the alfalfa ET was mostly similar to, and occasionally exceeded, NWS Class A pan evaporation at Kimberly, ID.

Evett et al. (2000) tested data calculated using a P-M reference ET equation against 1998 measured alfalfa ET for days when leaf area index was >3, while omitting days when the crop was not well-watered (drying period before harvest), when the crop was lodged, and when irrigation or rainfall compromised the integrity of the water balance calculations for measured ET. They found that ET estimated using daily weather data overestimated daily ET by about 1 mm per day on average ($ET_{P\text{-}M}$ = 1.02 + 0.97 ET, SE = 0.79 mm, r^2 = 0.90).

Equilibrium and Imposed Evapotranspiration

Equilibrium ET (ET_{eq}) as calculated using the decoupling and energy balance terms of the M-J model (Eq. [1]) was fairly stable at an average of 4.4 ($\pm$0.6) mm d^{-1} during the selected days (Fig. 6), contributing an average of 39% to ET_{24}. This reflected the fairly similar amount of solar irradiance during those days that is typical for summer at the research location, which averaged 29.5 ($\pm$1.5) MJ m^{-2} d^{-1} during these days. At most, summed daily ET_{eq} was about 55% of ET_{24}. Imposed ET (ET_{imp}) as calculated using the decoupling and vapor transfer terms of Eq. [1] ranged from 46% (3.2 mm) of 7.0 mm ET_{24} on DOY 157 to 75% (13.2 mm) of 17.6 mm ET_{24} on DOY 164.

Equilibrium ET resulted from positive AE fluxes to the surface, which occurred primarily during daylight hours. On a day with lower ET such as DOY 155 (ET_{24} = 7.9 mm d^{-1}), ET_{eq} was as much as 91% of hourly ET during the period when both VPD and wind speed were moderate (Fig. 7). However, when both wind speed and VPD increased, ET_{imp} and ET also increased sharply as ET_{eq} declined along with AE. The contributions to ET_{24} by ET_{imp} and ET_{eq} were equal by the end of the 24 h. On a day with extreme ET such as DOY 164 (ET_{24} = 17.6 mm), ET_{eq} was never more than 36% of the hourly ET rates, which peaked at 1.7 mm h^{-1} (Fig. 8). By the end of DOY 164, cumulative ET_{eq} was 4.4 mm and ET_{imp} was 13.2 mm.

Imposed ET losses continued after ET_{eq} ceased on all days evaluated (e.g., Fig. 7 and 8) from midnight to about 0500 and about 1900 to the following midnight ($ET_{imp\text{-}night}$). For this time period (no ET_{eq}), $ET_{imp\text{-}night}$ ranged from 0.7 mm (9%) of 8.0 mm ET_{24} on DOY 160 to 3.0 mm (21%) of 14.1 mm ET_{24} on DOY 173 (Fig. 9), with an average ET_{night} of 1.4 ($\pm$ 0.7) mm. Tolk et al. (2006) reported that measured nighttime ET of irrigated alfalfa near Bushland, TX, could approach 2 mm. Rosenberg (1969b) noted that nocturnal ET by alfalfa could be as much as 1 mm in Nebraska.

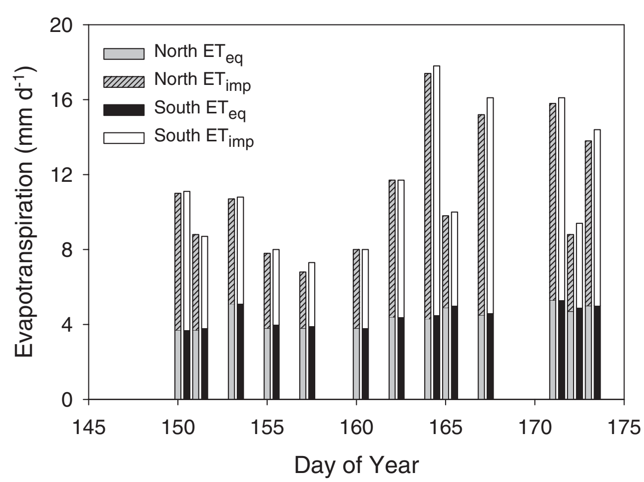

Fig. 6. Daily evapotranspiration (ET) partitioned into the equilibrium ET (ET_{eq}) and imposed (ET_{imp}) contributions as stacked bar graphs for the north and south lysimeters.

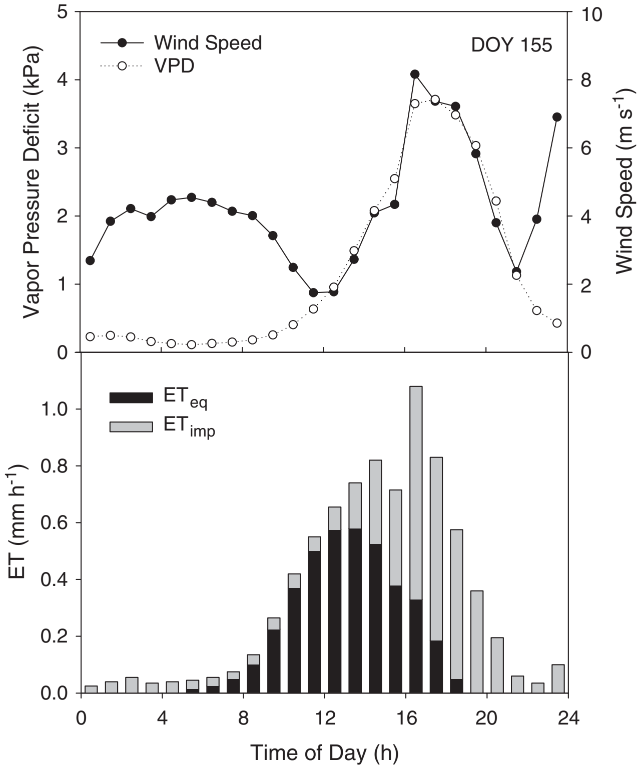

Fig. 7. Changes in vapor pressure deficit (VPD) and wind, and partitioning between equilibrium evapotranspiration (ET_{eq}) and imposed ET (ET_{imp}) as stacked bar graphs on day of year (DOY) 155.

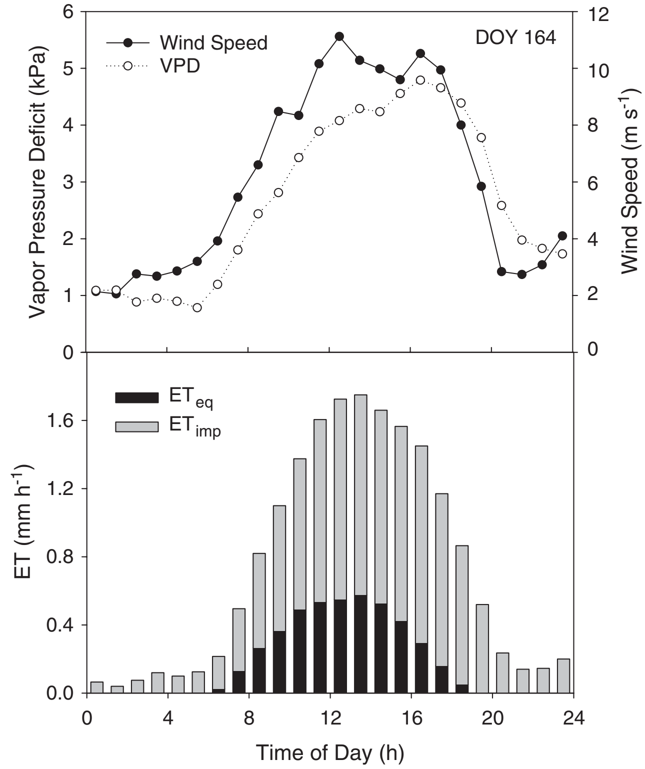

Fig. 8. Changes in vapor pressure deficit (VPD) and wind, and partitioning between equilibrium evapotranspiration (ET_{eq}) and imposed ET (ET_{imp}) as stacked bar graphs on day of year (DOY) 164.

Sensible Heat Flux

Available energy had a fairly stable mean of 16.2 ($\pm$1.2) MJ m^{-2} d^{-1}, which converts using λ to an average of 6.6 ($\pm$0.5) mm d^{-1}, whereas λE ranged from -17.1 to -43.0 MJ m^{-2} d^{-1} representing ET losses of 7 to 17.6 mm d^{-1} (Fig. 10). The additional daily energy consumed by λE was supplied by H input ranging from 1.3 MJ m^{-2} d^{-1}, or 8% of the energy used in λE on DOY 157, to 25.7 MJ m^{-2} d^{-1}, or 60% of the energy used in λE on DOY 164, with a mean H input of 11.5 ($\pm$7.9) MJ m^{-2} d^{-1}. The fairly stable amounts of AE show that the extreme ET events on DOY 164, 167, 171, and 173 were associated with large influxes of sensible heat where H contributed more than 54% of the energy used in λE. An examination of the energy balance on DOY 155 (Fig. 11) showed that H was negative for much of the daytime hours such that AE + $H \leq$ AE. The H flux became positive as wind speed and VPD sharply increased around 1600 h (Fig. 7), which was then followed by increased λE. On DOY 164, H input to the surface energy balance was positive throughout the 24-h period, and was greatest in the afternoon hours (Fig. 11). At night, when AE was negative, H would remain positive and λE continued (e.g., Fig. 7, 8, 9, 11).

Brakke et al. (1978) reported sensible heat supplied from 15 to 50% of energy consumed by λE of alfalfa in Nebraska, which is similar in range to our values. Adbel-Aziz et al. (1964) found that measured ET of alfalfa reached maximums of 71% more than measured R_n in Utah due to advected heat. The ratios of $\lambda E/(R_n + G)$ for irrigated alfalfa during a drought period in Nebraska that were summarized by Rosenberg and Verma (1978) ranged from 1.3 to 3.0. The ratios for the evaluation period at Bushland ranged from 1.1 to 2.5.

Local and Regional Advection

Sources of advection in this analysis could be either local or regional. A study by Brakke et al. (1978), which attempted to separate local and regional advection effects on ET of irrigated alfalfa, suggested that local

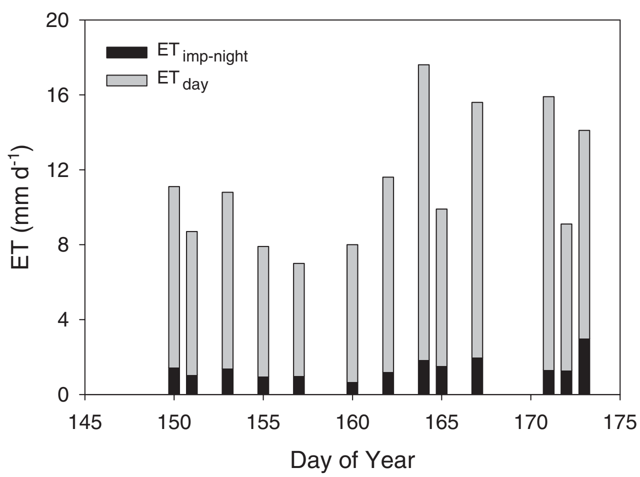

Fig. 9. Partitioning of daily evapotranspiration (ET) into daytime losses (ET_{day}) and nighttime losses due to ET_{imp} only ($ET_{imp\text{-}night}$).

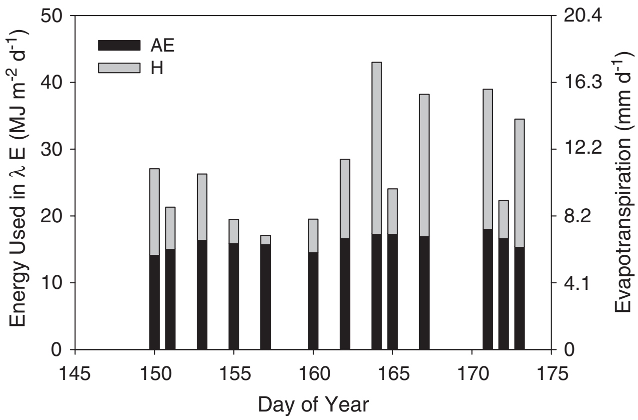

Fig. 10. Energy used in latent heat (λE) supplied by available energy (AE) and sensible heat (H) and equivalent evapotranspiration calculated using the latent heat of vaporization (2.45 MJ kg^{-1}).

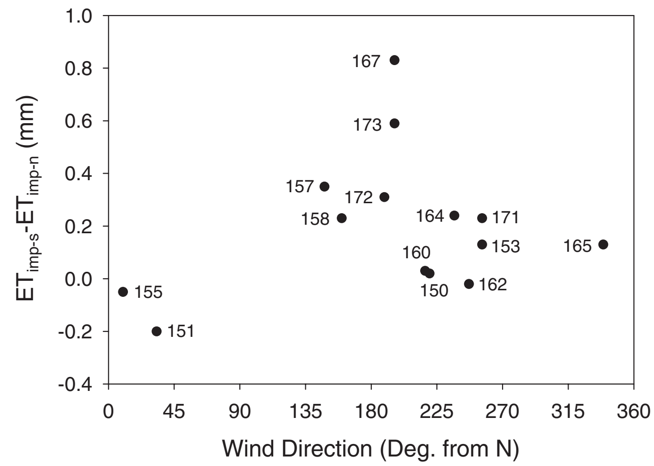

Fig. 12. Difference between imposed evapotranspiration from the south lysimeter (ET_{imp-s}) and the north lysimeter (ET_{imp-n}) in relation to wind direction.

advection effects were greatly reduced within 100 m downwind of the leading edge transition between a nonirrigated and irrigated field. However, λ*E* still exceeded AE due to regional advection.

The impact of local advection was investigated by comparing the magnitude of the differences between ET_{imp} of the north (ET_{imp-n}) and the south (ET_{imp-s}) lysimeters in relationship to fetch as determined by the prevailing wind direction. The assumption was that the effect of local advection on ET would be reduced as the fetch increased. When the wind direction was from the south, the fetch distance to the south lysimeter was 112 m and to the north lysimeter was 338 m (Fig. 3) (or in reverse if wind direction was from due north). But, when the wind was from the easterly or westerly directions, the fetch to the two lysimeters was roughly equivalent.

When the wind direction was primarily southerly, ET_{imp-n} was lower than ET_{imp-s} by 0.83 mm d^{-1} on DOY 167 and 0.59 mm d^{-1} on DOY 173 (Fig. 12). On DOY 167, the wind blew from between the SSW and SSE directions for 75% of the time, with 40% of the wind speeds averaging between 7 and 11 m s^{-1} (Fig. 13). On DOY 173, the wind blew from between the SSW and SSE directions for 54% of the time, and from the SW to WNW for the remainder of the time. In contrast, the ET_{imp-n} was slightly larger than ET_{imp-s} on DOY 151 when wind direction was from the NE to NW for 40% of the day (Fig. 14). The difference in ET_{imp} between the two lysimeters on DOY 151 could possibly have been larger if the wind direction was as consistently from the

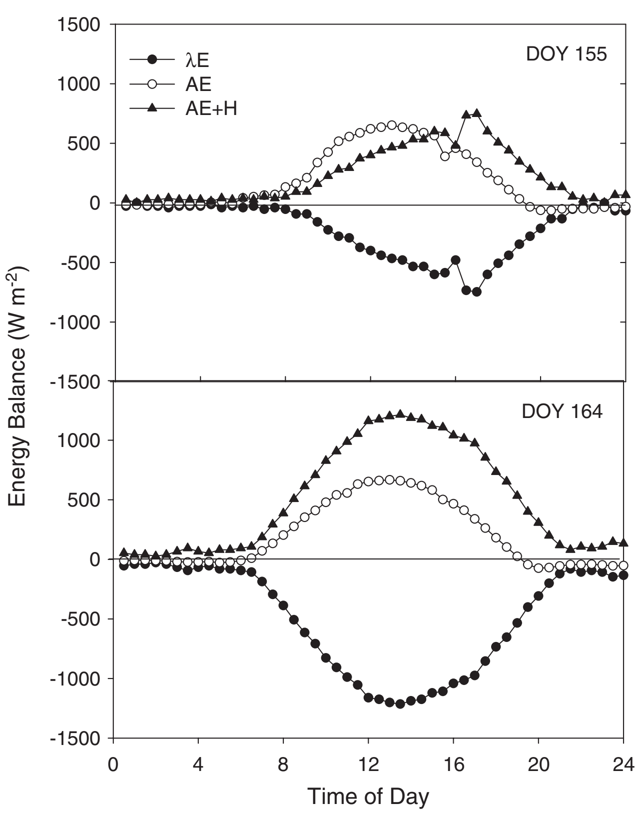

Fig. 11. Energy balance fluxes on day of year (DOY) 155 and 164, including latent heat (λ*E*), available energy (AE), and λ*E* + sensible heat (*H*).

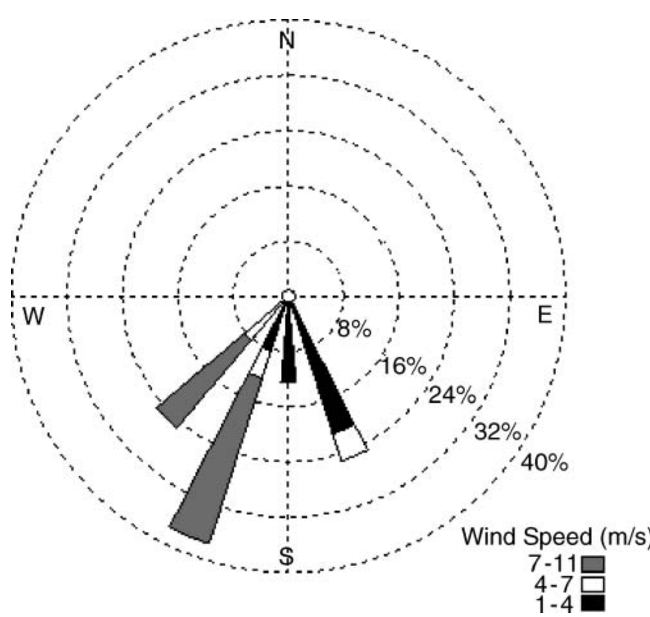

Fig. 13. Wind speed and wind direction analyses for day of year 167.

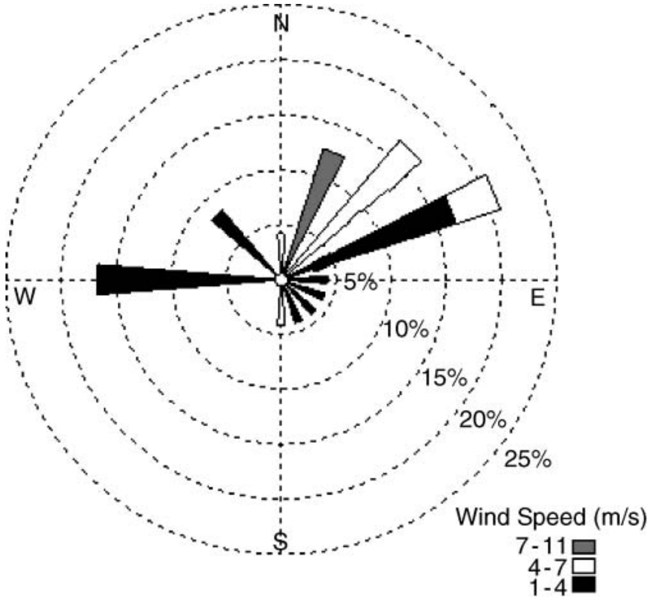

Fig. 14. Wind speed and wind direction analyses for day of year 151.

north as it was from the south on DOY 167. On most days, differences in ET_{imp} ranging from 0 and 0.4 mm d^{-1} were maintained between the two lysimeters as fetch decreased due to the prevailing SW winds (Fig. 1).

However, differences in fetch did not greatly reduce the contributions to ET_{24} by ET_{imp}, indicating the dominance of regional advection. The percentage that ET_{imp} contributed to total ET remained high, e.g., on DOY 167 the $ET_{imp\text{-}n}$ was 10.7 mm, which was 70% of the ET_{24} of 15.2 mm and on DOY 151 the $ET_{imp\text{-}s}$ was 4.9 mm, or 56% of the ET_{24} of 8.7 mm.

Brakke et al. (1978) found that regional advection was greatest on days with strong winds, whereas local advection was independent of wind speed. They also found that the drier the air, the greater the advection of sensible heat. Similar results occurred in this analysis, which covered a range of both VPD and wind speed. Sensible heat flux increased with both wind and VPD (Fig. 15), which, given the relatively stable amount of available energy, resulted in increased ET as the result of largely regional thermal energy to the crop from the mesoscale atmospheric conditions.

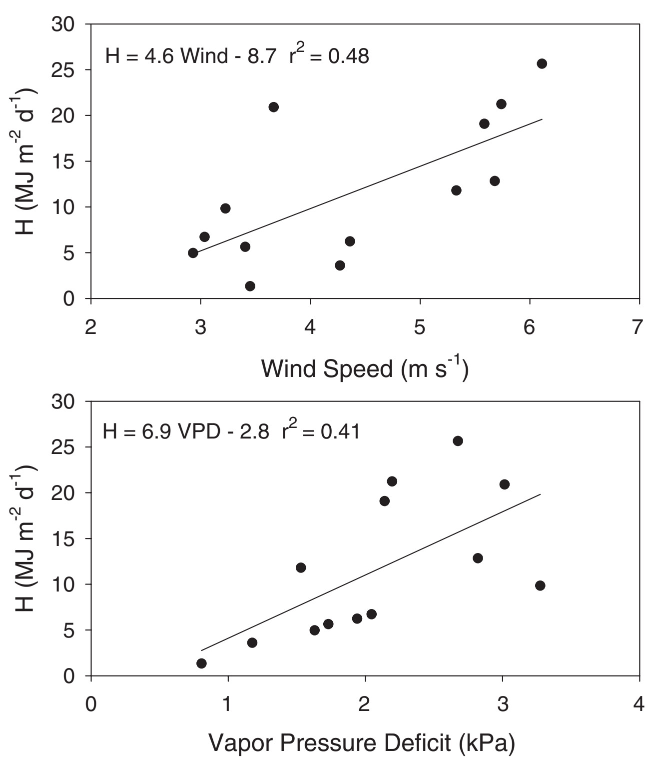

Fig. 15. The relationships between wind speed and sensible heat flux (*H*), and vapor pressure deficit (VPD) and *H*.

CONCLUSIONS

Impact of advection on daily ET of irrigated alfalfa was examined over a range of microclimatic conditions that varied from moderate VPD and wind speed when ET_{24} was <10 mm d^{-1} to extreme events with large VPD and wind speed values when ET_{24} exceeded 16 mm d^{-1}. The partitioning of ET into ET due to available energy from net radiation and soil heat flux inputs as $R_n + G$, or ET_{eq}, and ET due to regionally set atmospheric deficits imposed on the crop through turbulent mixing by wind, or ET_{imp}, showed that ET_{imp} could be as much as 75% of total ET, with an average of 61%. Overnight ET losses as ET_{imp} could be as much as 3.0 mm. The additional energy needed in ET was provided by sensible heat gain, which averaged 38% of that used in λE, and was as large as 60%. If fetch was increased, the local advection contributions to ET were reduced but regional advection still dominated ET as ET_{imp}. Smaller wind speeds and VPD tended to modify the effects of regional advection on irrigated alfalfa ET, but the advective enhancement of ET was restored when both VPD and wind speed increased. Advective enhancement of ET plays a significant role in the water balance of the semiarid region of the southern High Plains.

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